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# **Resonant Interband Tunneling Diodes for High Performance Electronics**

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HRL Laboratories**

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# Acknowledgements

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HRL Laboratories

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# RITD-based circuits Outline

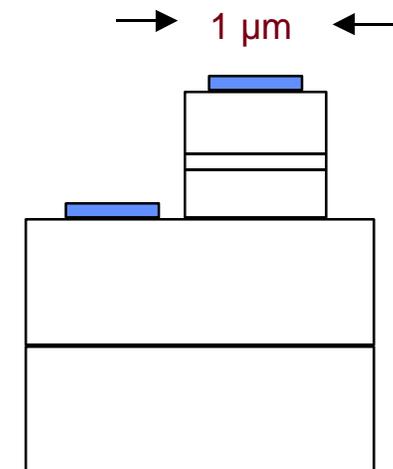
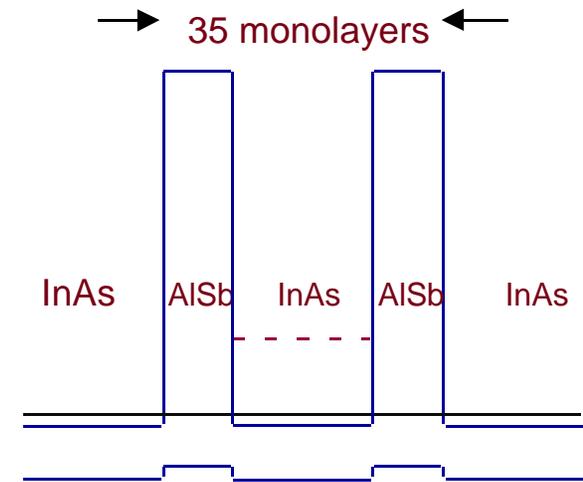
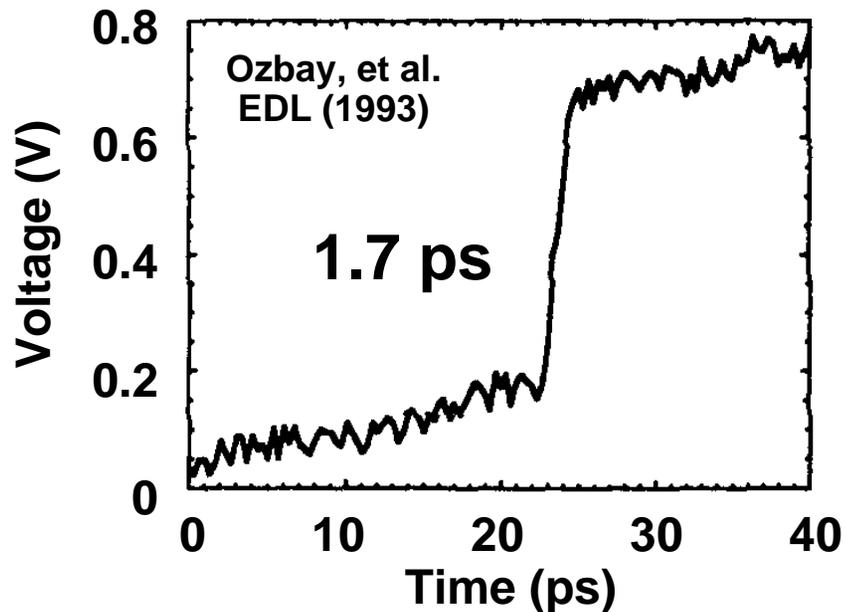
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- **Advantages of 6.1Å resonant tunneling devices**
- **Integration with advanced transistors**
- **Circuit concepts, demonstrations**
- **Sensor-based materials growth**

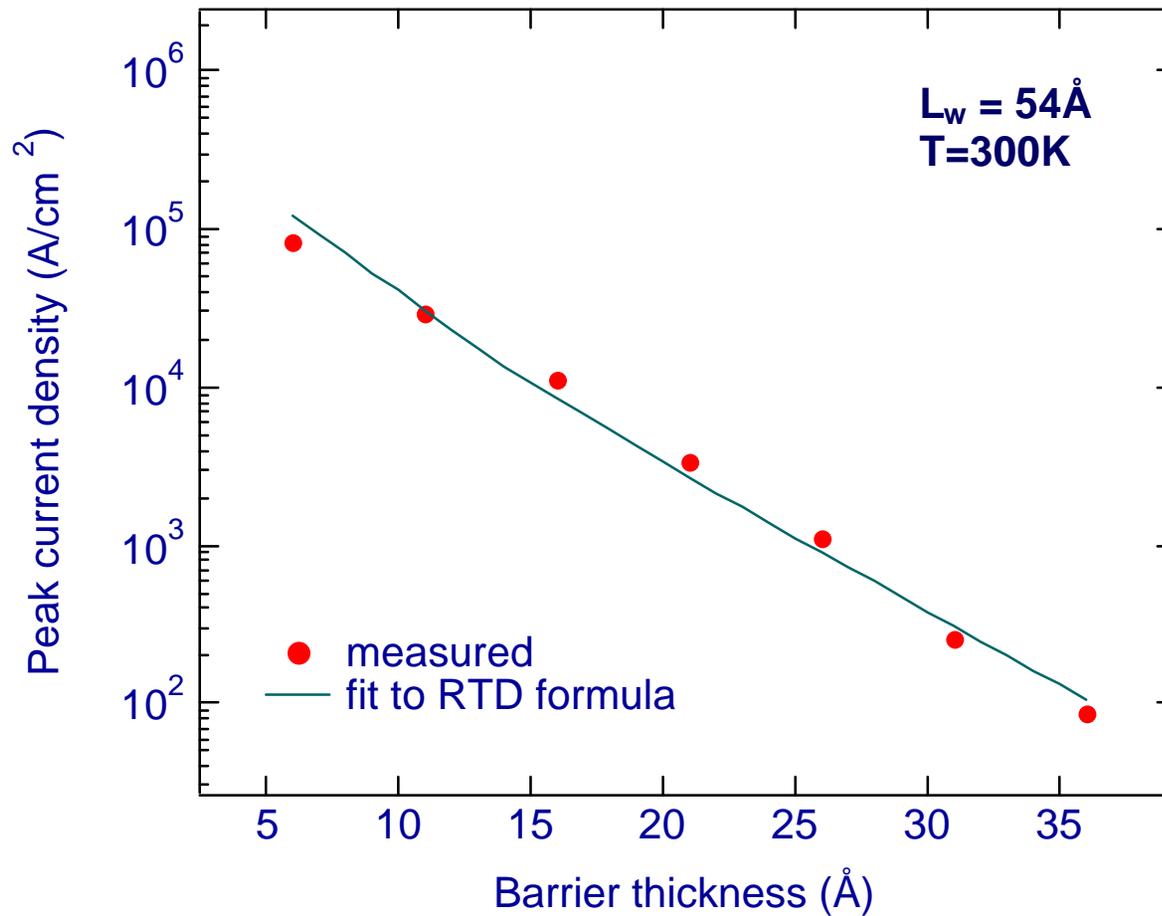
# Why use RTDs?

- Ultrafast operation (e.g., 1 ps switch,  $f_{\max} > 1\text{THz}$ )
- Low power consumption
- Small device footprint
- Reduced device count
- Increased functionality





## RITDs OPERATE OVER A WIDE CURRENT DENSITY RANGE

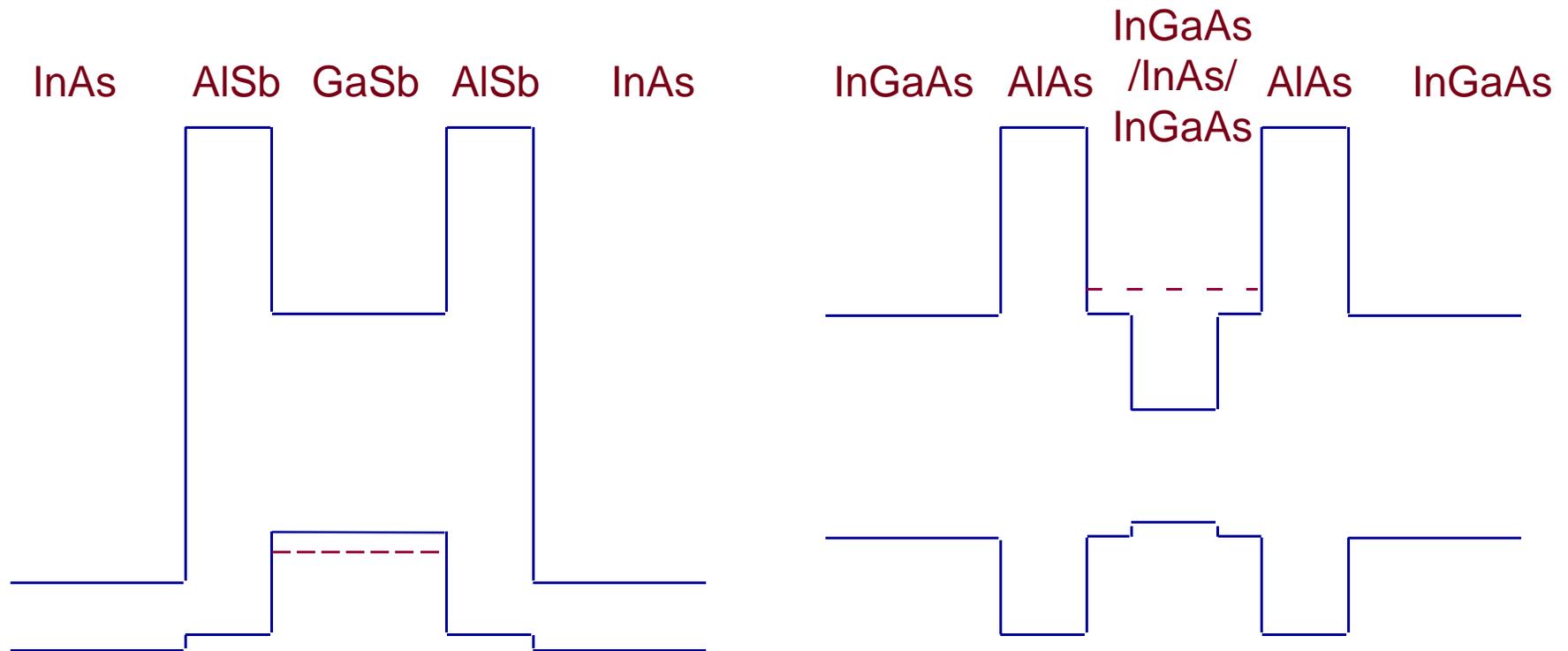


- $P/V > 8$  over entire  $J_p$  range
- Speed index =  $J_p/C_j$
- Characteristics relatively insensitive to  $L_w$
- Normally deposited on GaAs

# Advantages of RITDs for high speed, low power



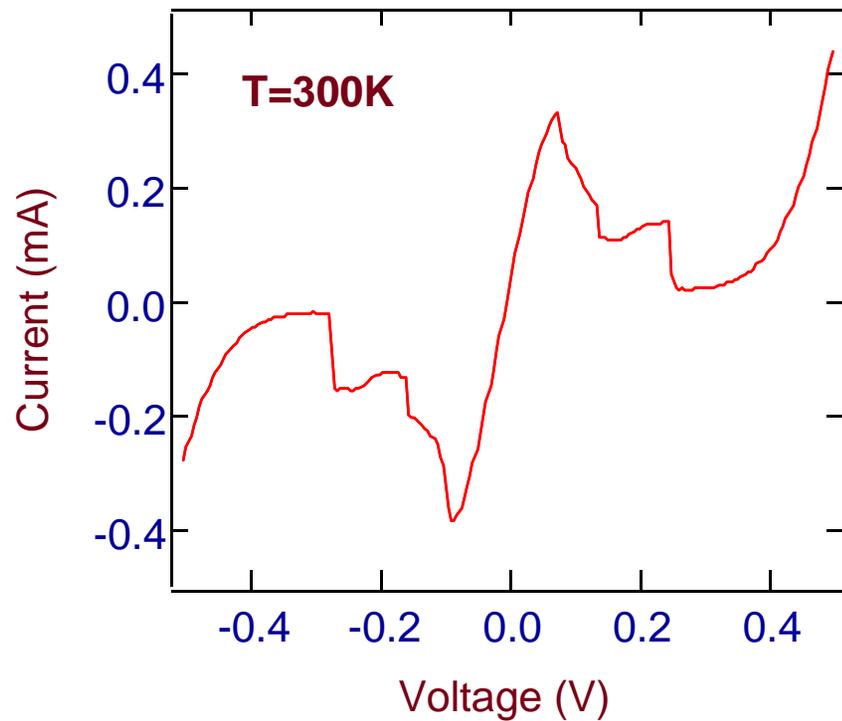
- Low  $V_p$ , low  $V_f$
- Tremendous flexibility for band diagram engineering
- “Perfect” ohmic contacts [InAs(n) and GaSb(p)]



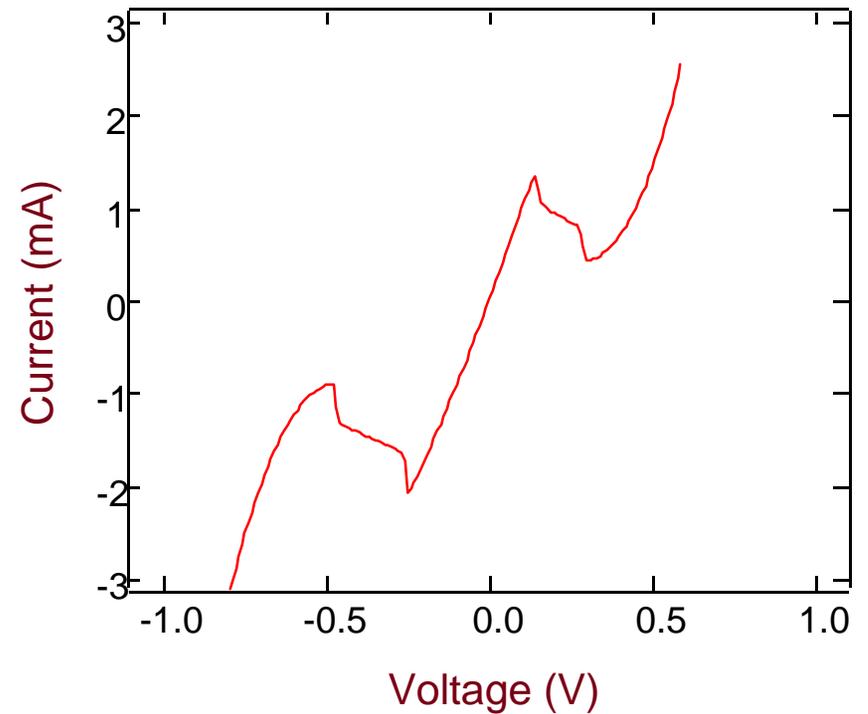
# Comparison of RITD and RTD I-V characteristics for $V_p=0.1$



## RITD



## RTD



# Integration of RITDs with HFETs



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**Integration with transistors is a requirement for a complete IC technology based on RITDs**

**HFETs provide:**

- **Input/output isolation**
- **Controllable gain**

**RITDs provide:**

- **Increased functionality (important at 100 GHz)**
- **Enhanced circuit speed**
- **Reduced power consumption**

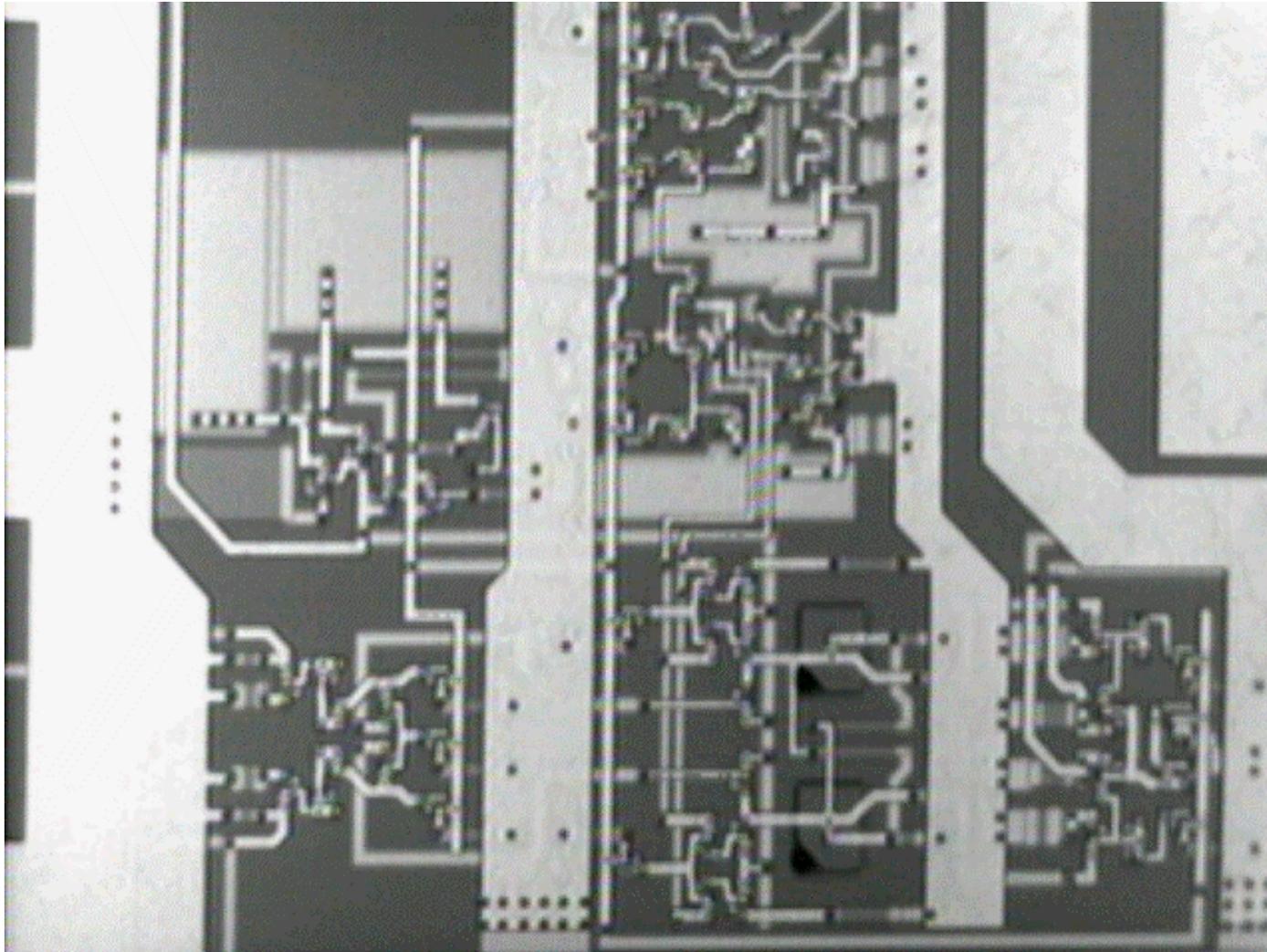
# Demonstrated RTD/transistor ICs on InP



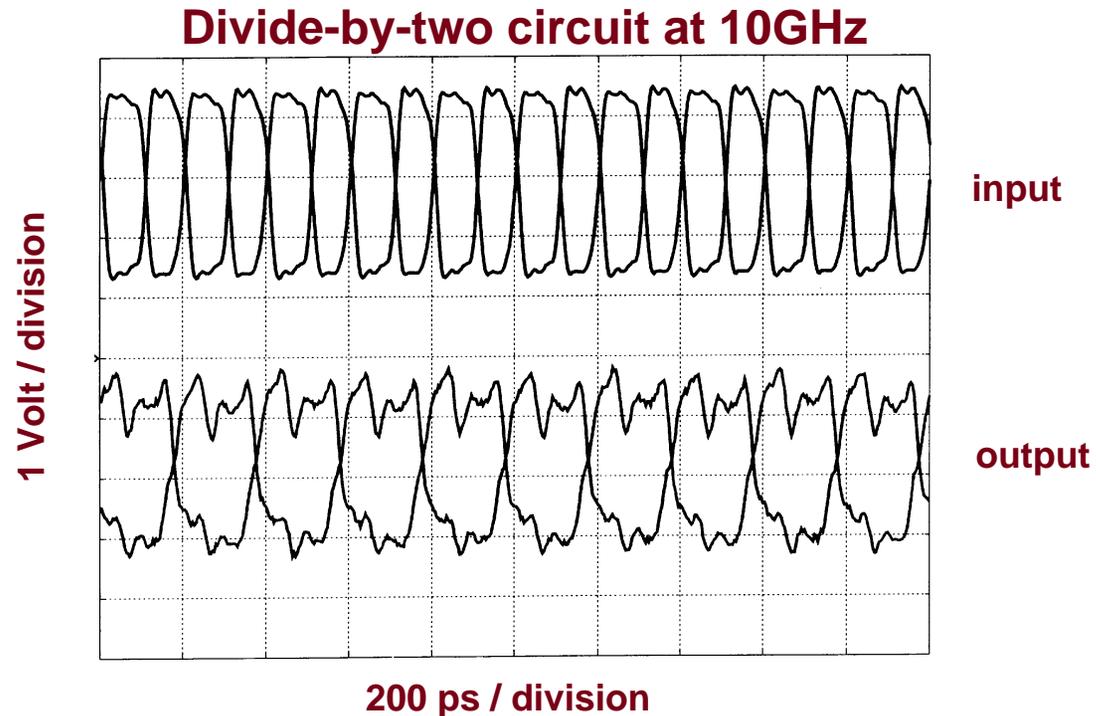
- 
- **80 Gb/s demultiplexer (NTT)**
  - **2 Gsps, 4-bit A/D Converter (Raytheon)**
  - **15 GHz frequency divider (HRL/Mayo)**



## Magnified view of latching comparator



# InP-based RTD/HBT ICs Demonstrated



- **Data buffers operational to 15GHz (60% duty cycle)**
- **Frequency dividers operational to 14GHz (12mW power)**
- **Ring oscillators operational to 11GHz (22mW power)**

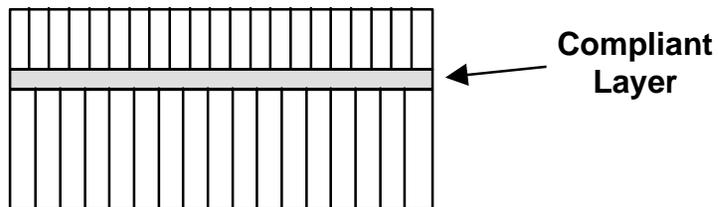
# High performance device trends



	Si CMOS	GaAs MESFET	InP HBT or FET	InAs/GaSb/AlSb
Integration level	$10^7$	$10^5$	$10^3$	10
$\mu_e$ (cm <sup>2</sup> /V-s)	1300	5000	10,000	20,000
$f_t$	10 GHz	40 GHz	> 100 GHz	> 100 GHz
epi required?	no	no	yes	yes
wafer size	8"	6"	3"	6" (GaAs)
RTDs available?	no	no/yes	yes	yes

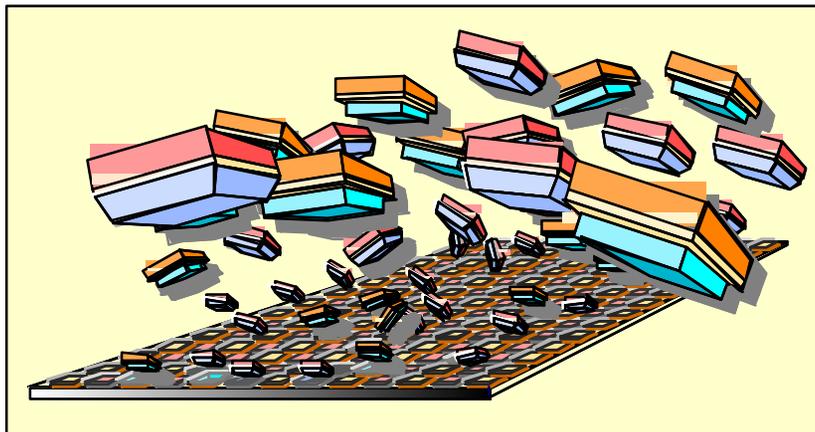
# IMPACT OF HETEROGENOUS INTEGRATION TECHNOLOGIES

## “Compliant Substrate” Allows Vertical Integration of Dissimilar Semiconductor Materials



## Technology Vision

- Integration of RTDs with commercial technology (CMOS, GaAs MESFET)
- Optoelectronic / electronic integration
- MEMS / electronic integration



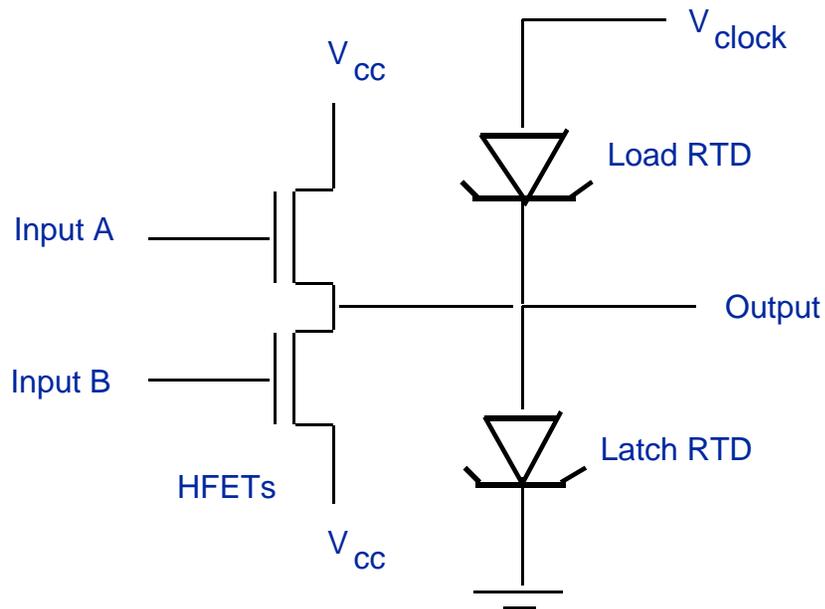
## Heterogeneous Integration of Microelectronic Assemblies

- Mass assembly of geometrically shaped micro-modules (devices)
- Delivered by fluid transport
- Self-assembled into matching companion sites on host substrate

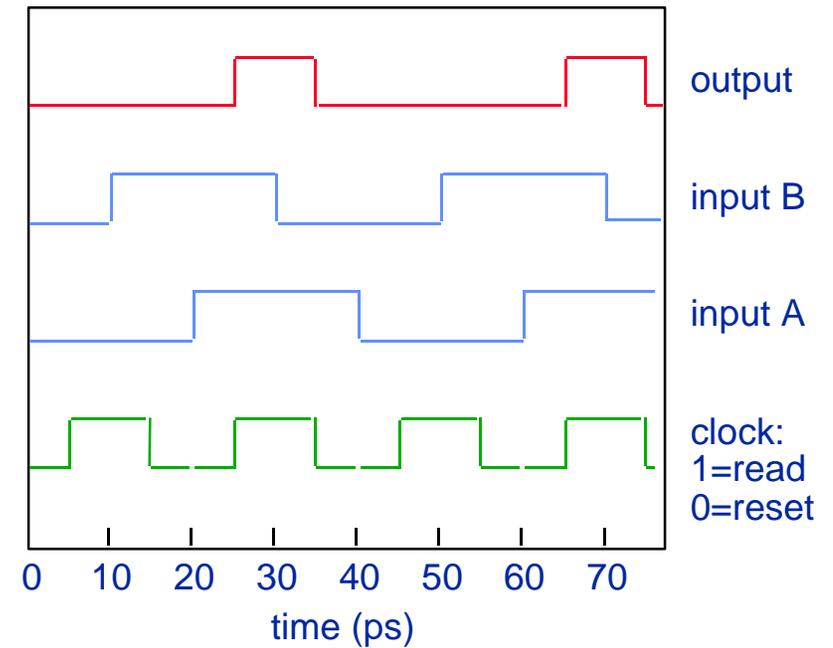
# CIRCUIT CONCEPTS - BISTABLE PAIR



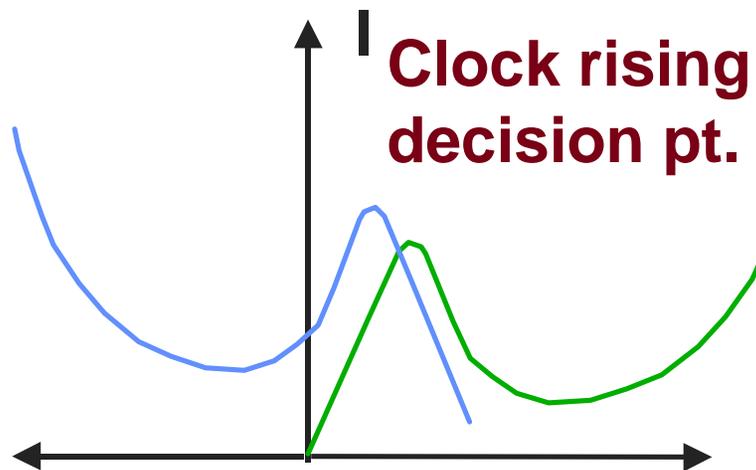
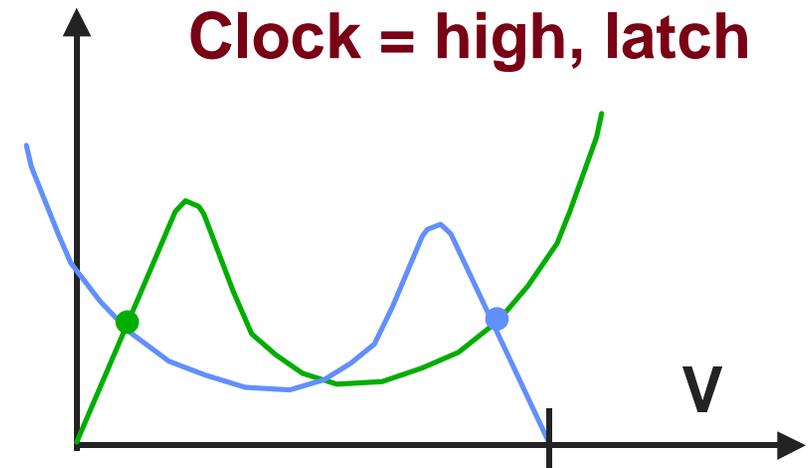
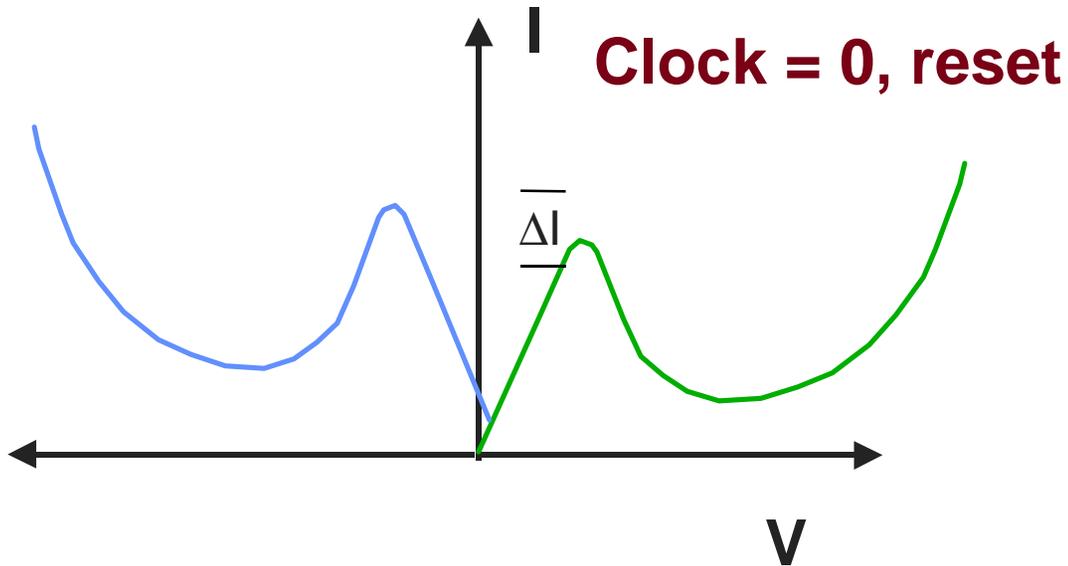
## Logic circuit element



## Schematic operation



# ANALYSIS OF BISTABLE PAIR



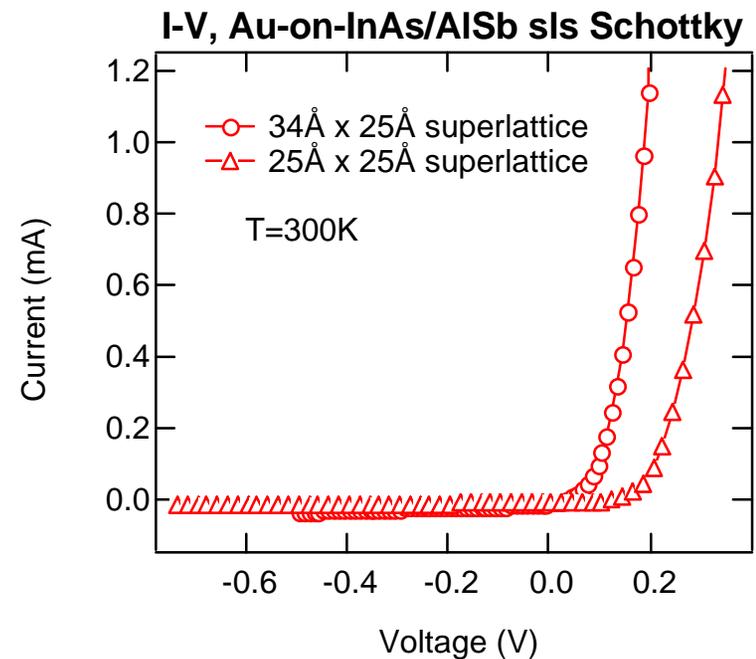
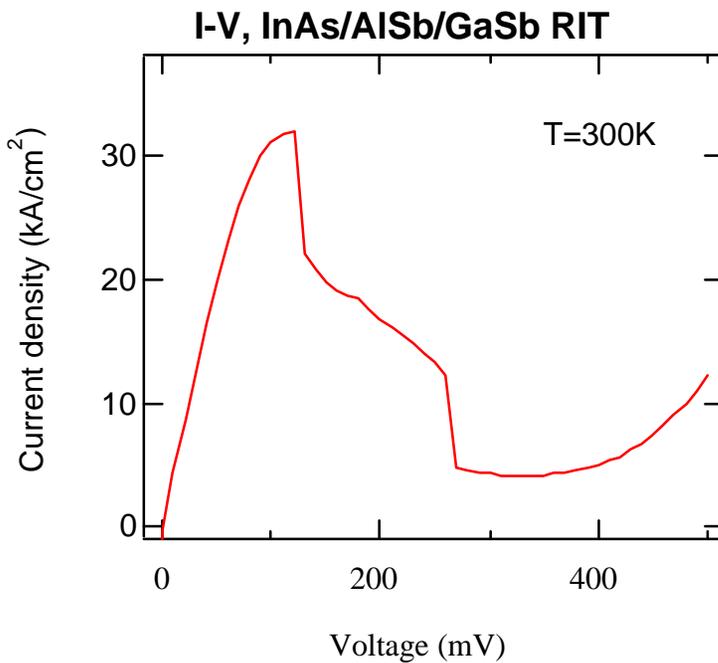
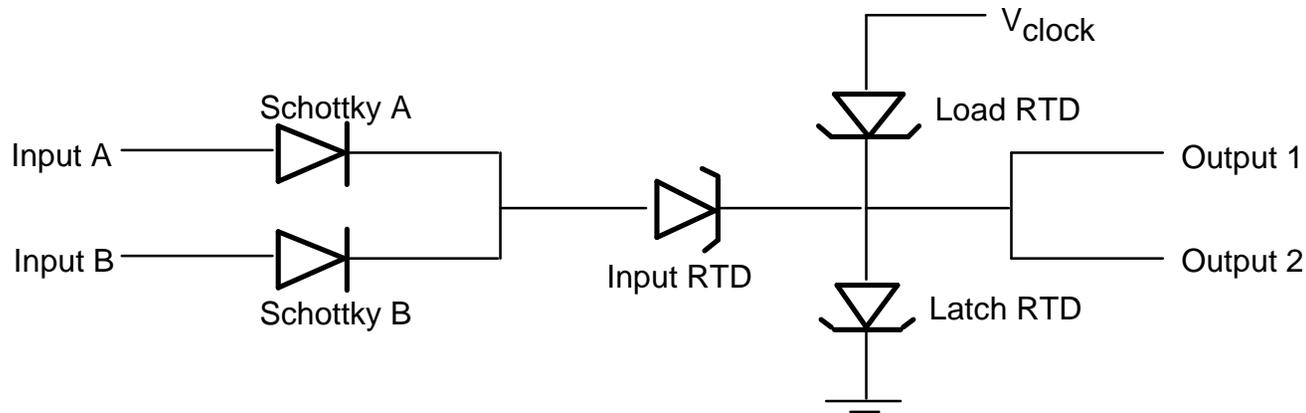
# CIRCUIT DEMOS BASED ON BISTABLE PAIR

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- **SRAM (Raytheon)**
- **100 Gb/s optical receiver (NTT)**
- **Logic family at 12 GHz (Mayo/HRL/Notre Dame)**

# Integrated InAs/AlSb/GaSb diode logic demonstrated (12GHz)

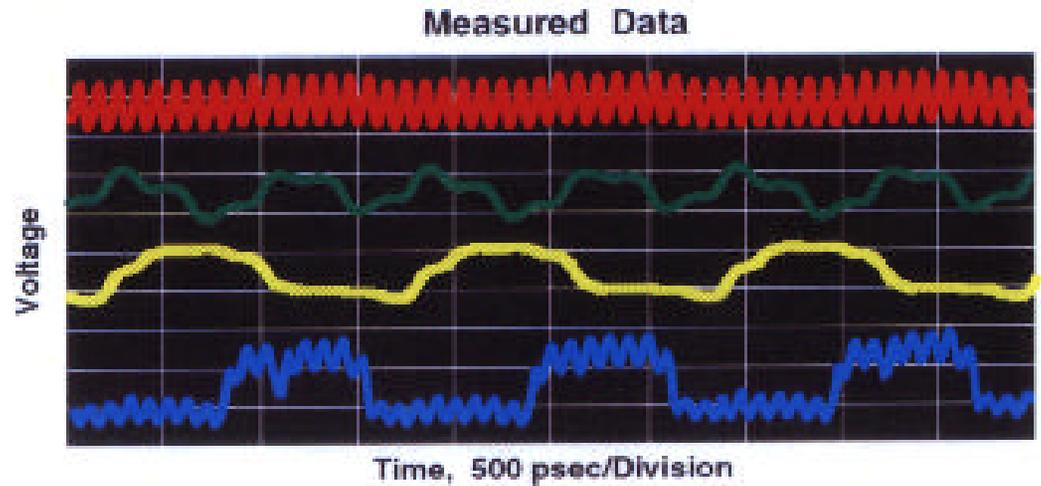


# Ultrafast Integrated InAs/AlSb/GaSb Logic Gates Demonstrated (12GHz clock)

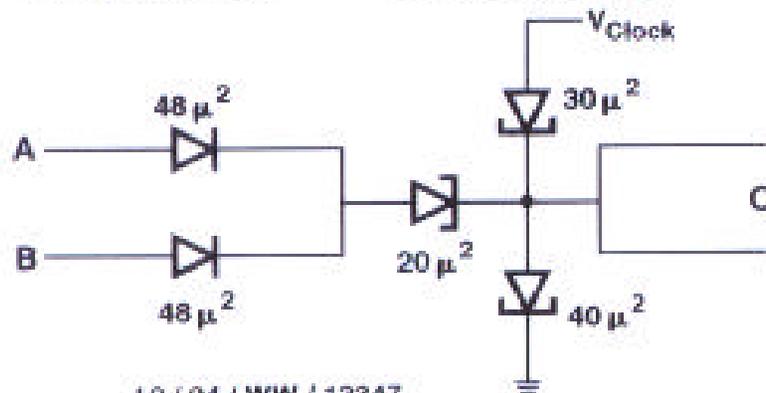


Truth Table

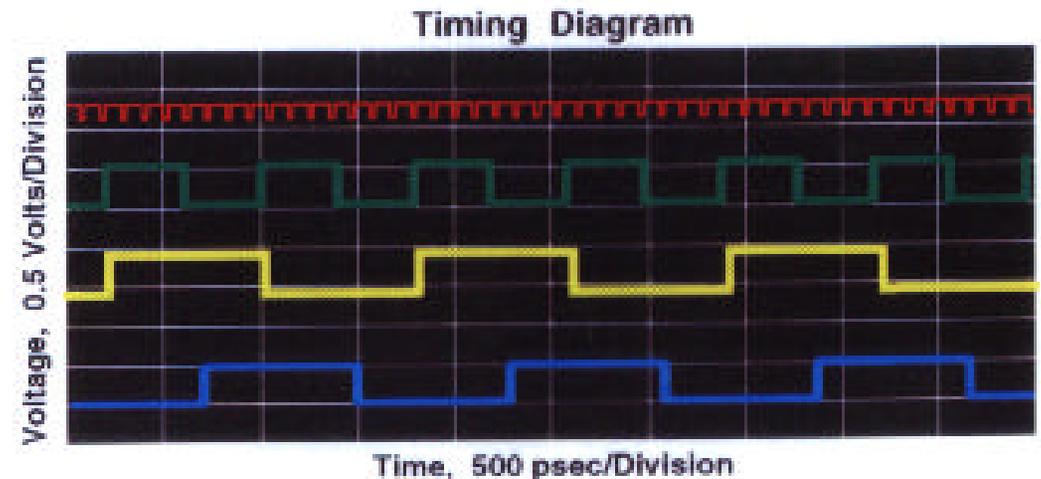
A	B	C
0	0	0
1	0	1
0	1	1
1	1	0



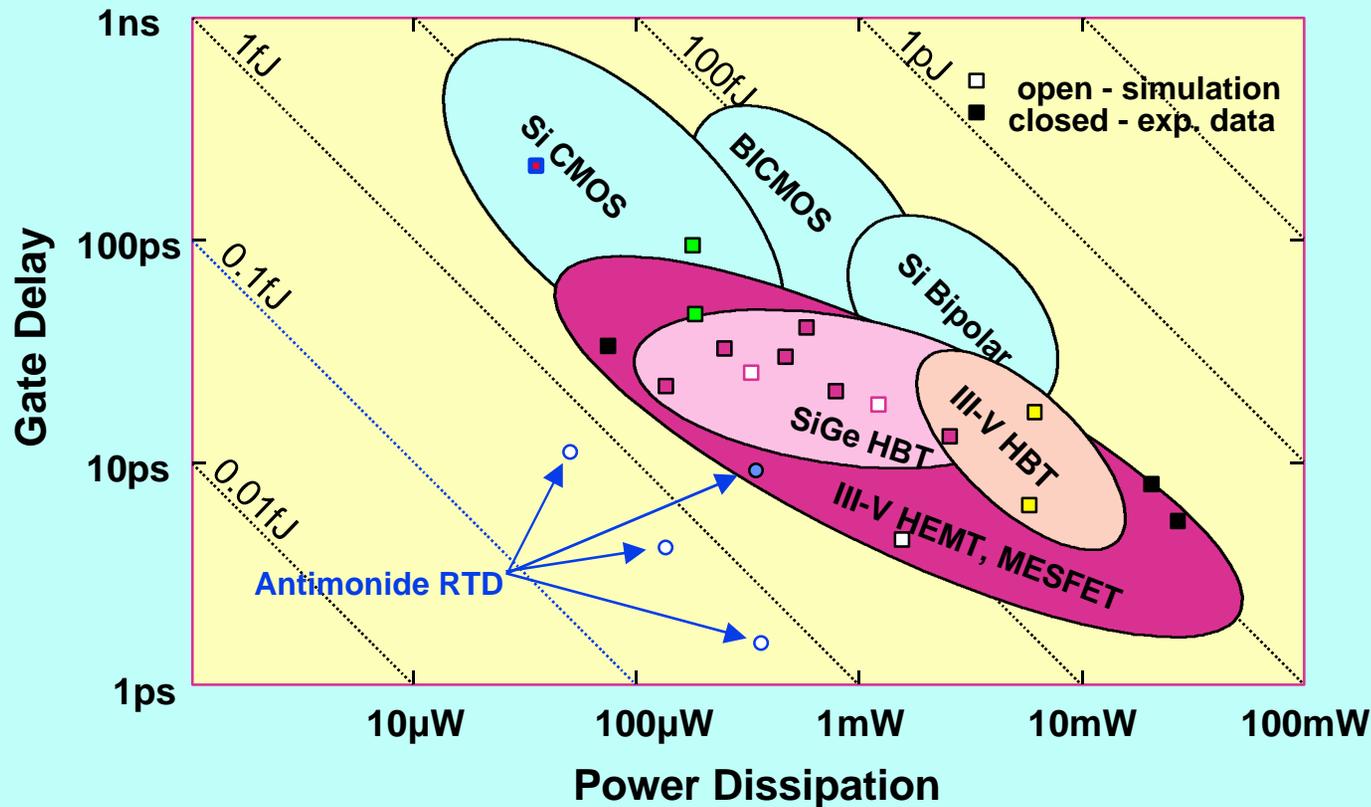
RTD/Schottky XOR Gate Schematic



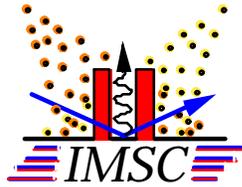
10 / 94 / WW / 12347



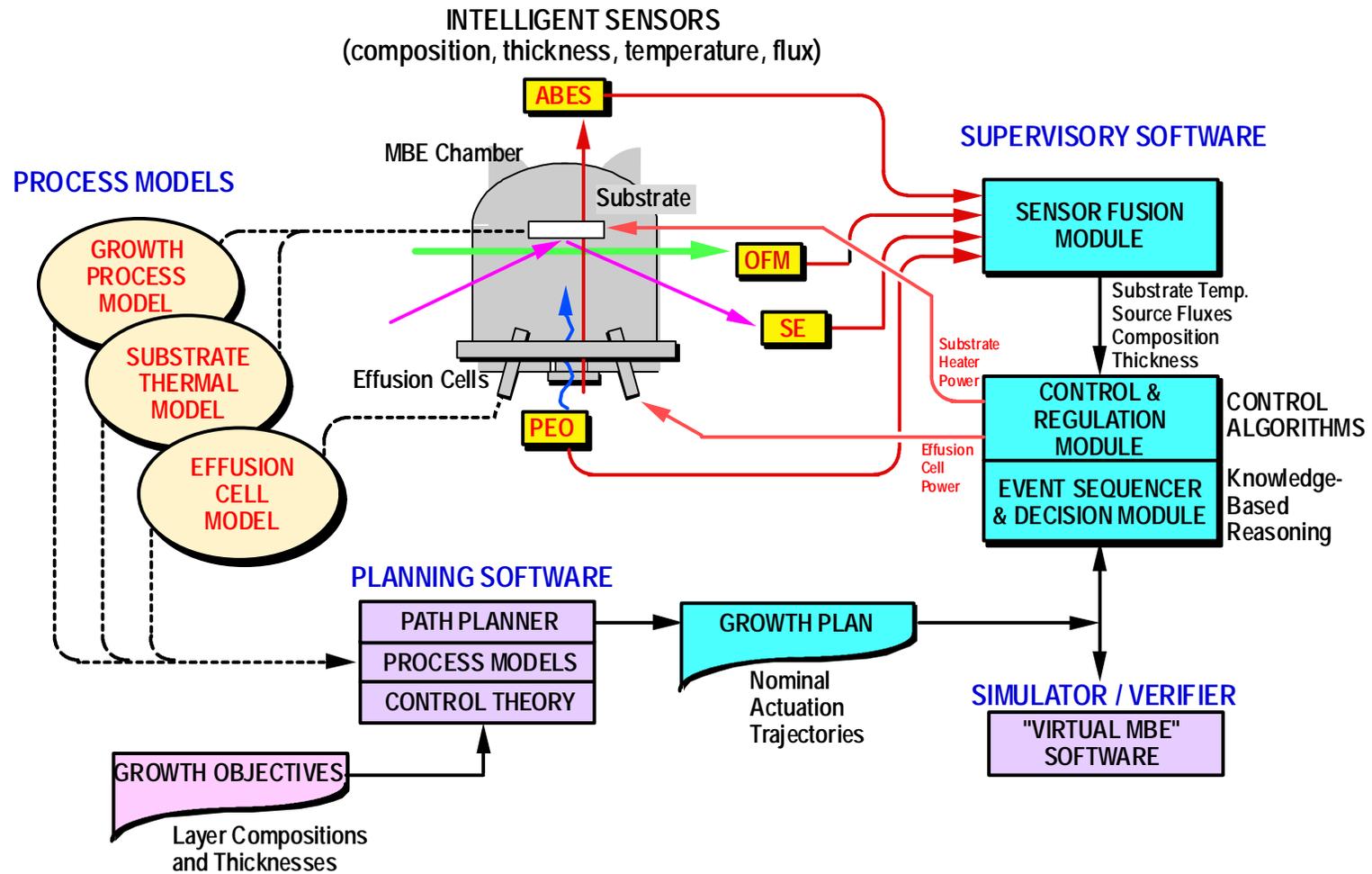
# Power - Delay Product for Digital IC Technologies

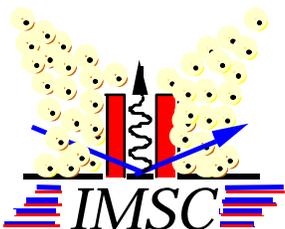


- data taken from U. König, et al., IEEE GaAs IC Symposium, pp14-18 (1995)
- Antimonide RTD data from W. Williamson et al., IEEE SSC **32**, 222(1997)
- Phillips, IEDM 95, p747; Siemens, op.cit. p739; NEC, IEDM 92, p. 397
- HRL, InP baseline and scaled process, 1997
- Vitesse FX and SCFX product data, GaAs MESFET, 1997
- Motorola, Complementary GaAs, GaAs IC Symp 95, p 18

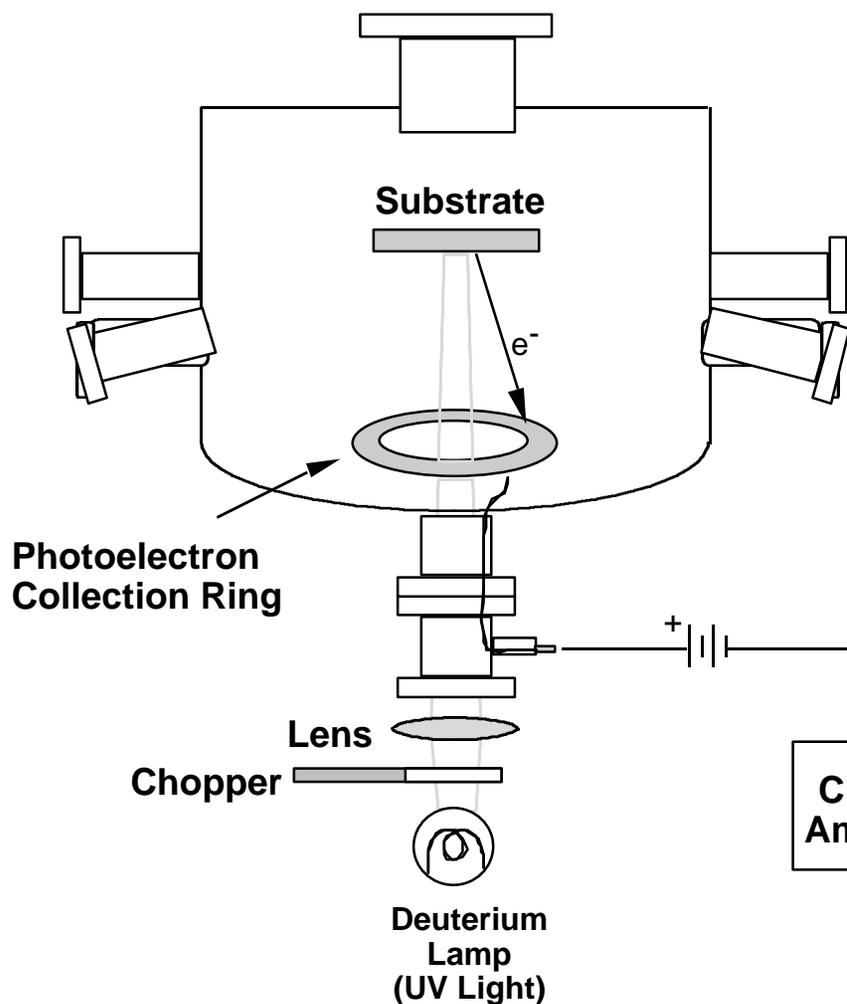


# INTEGRATED MULTI-SENSOR CONTROL SYSTEM FOR MBE

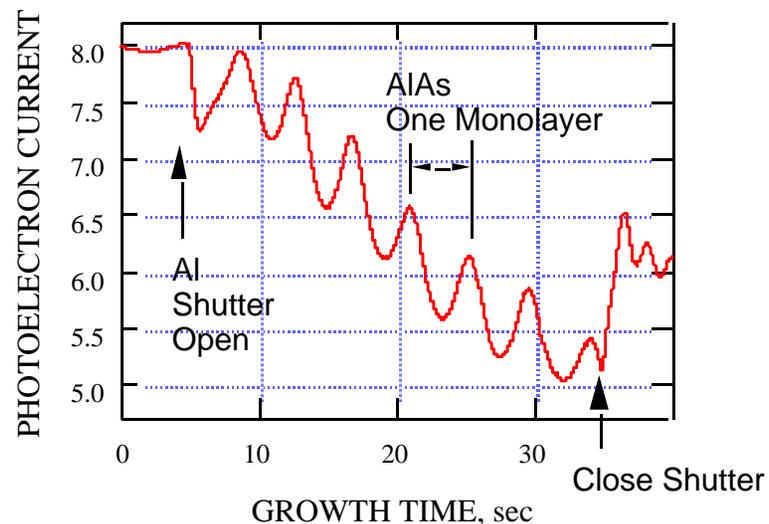




# PHOTOEMISSION OSCILLATION (PEO) SENSOR PROVIDES MONOLAYER THICKNESS MEASUREMENT DURING MBE GROWTH



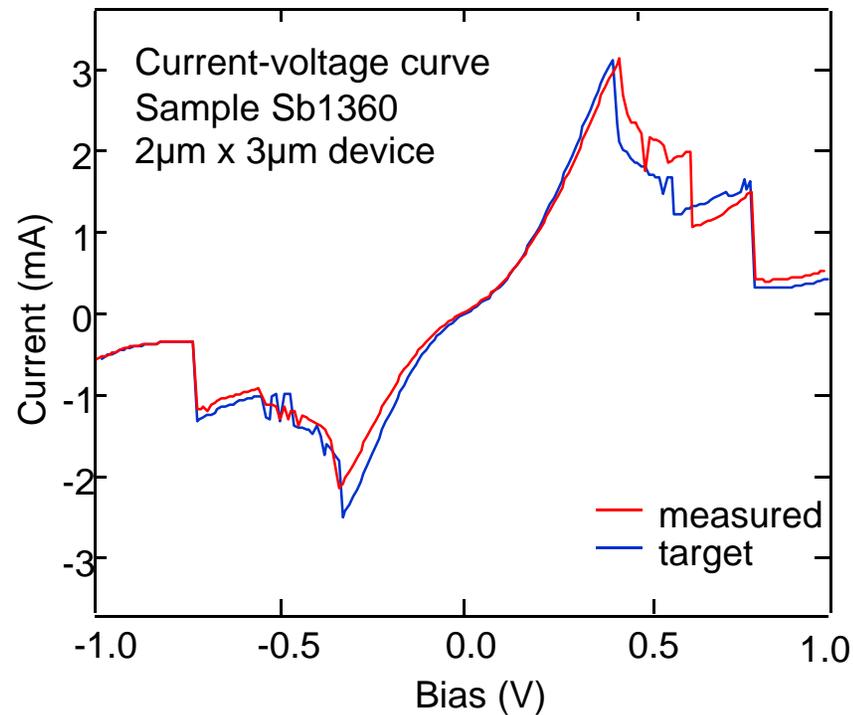
TOTAL PHOTOELECTRON CURRENT EXHIBITS OSCILLATIONS AS EACH MONOLAYER IS GROWN



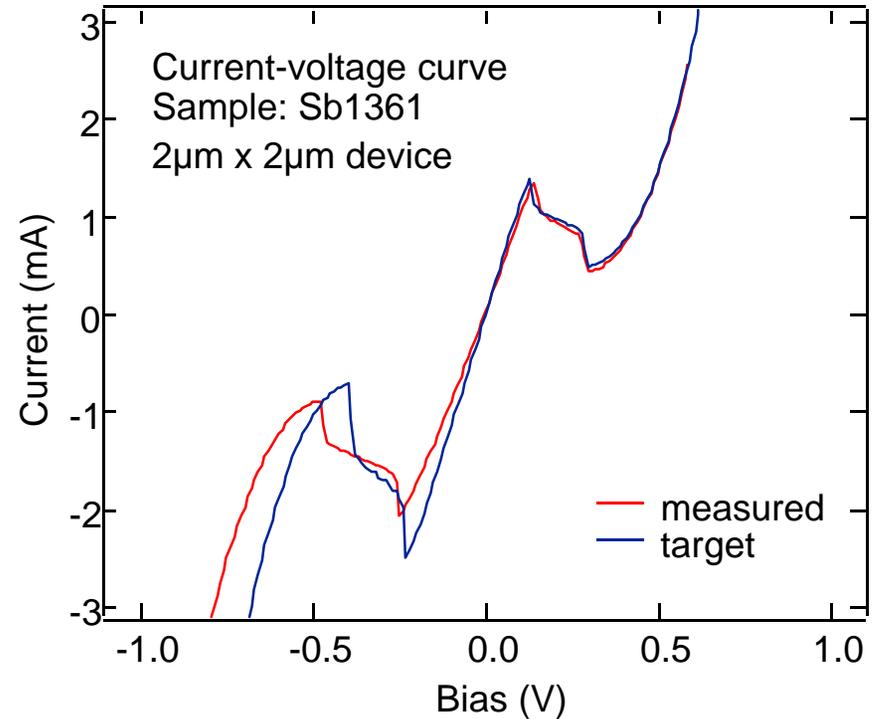
# Comparison Between Measured and Target RTD Current-Voltage Curves

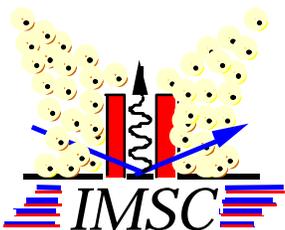


## VML RTD

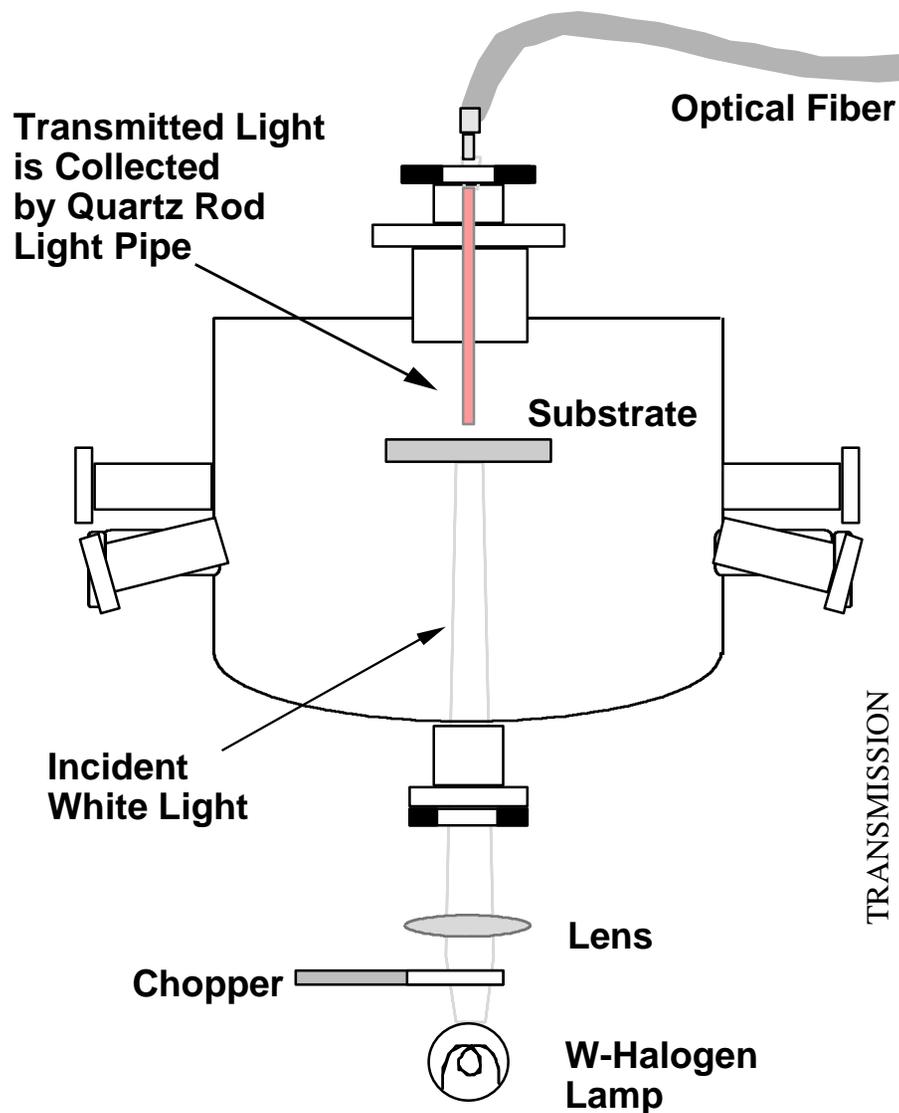


## CML RTD

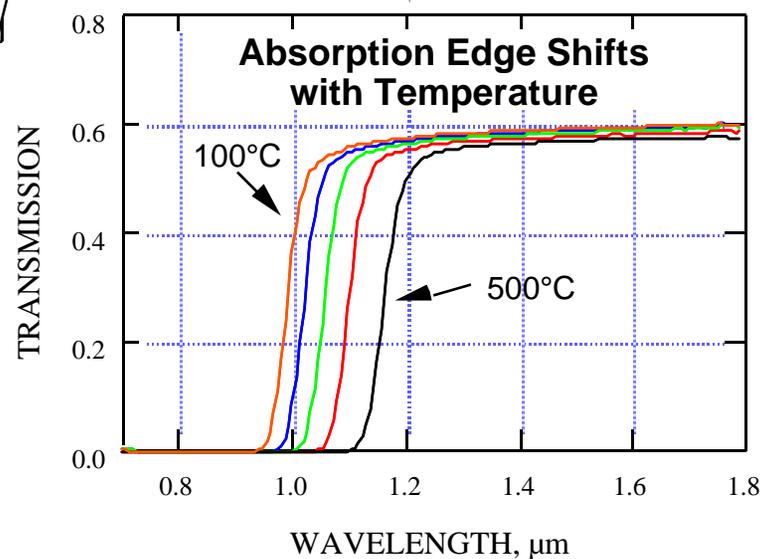




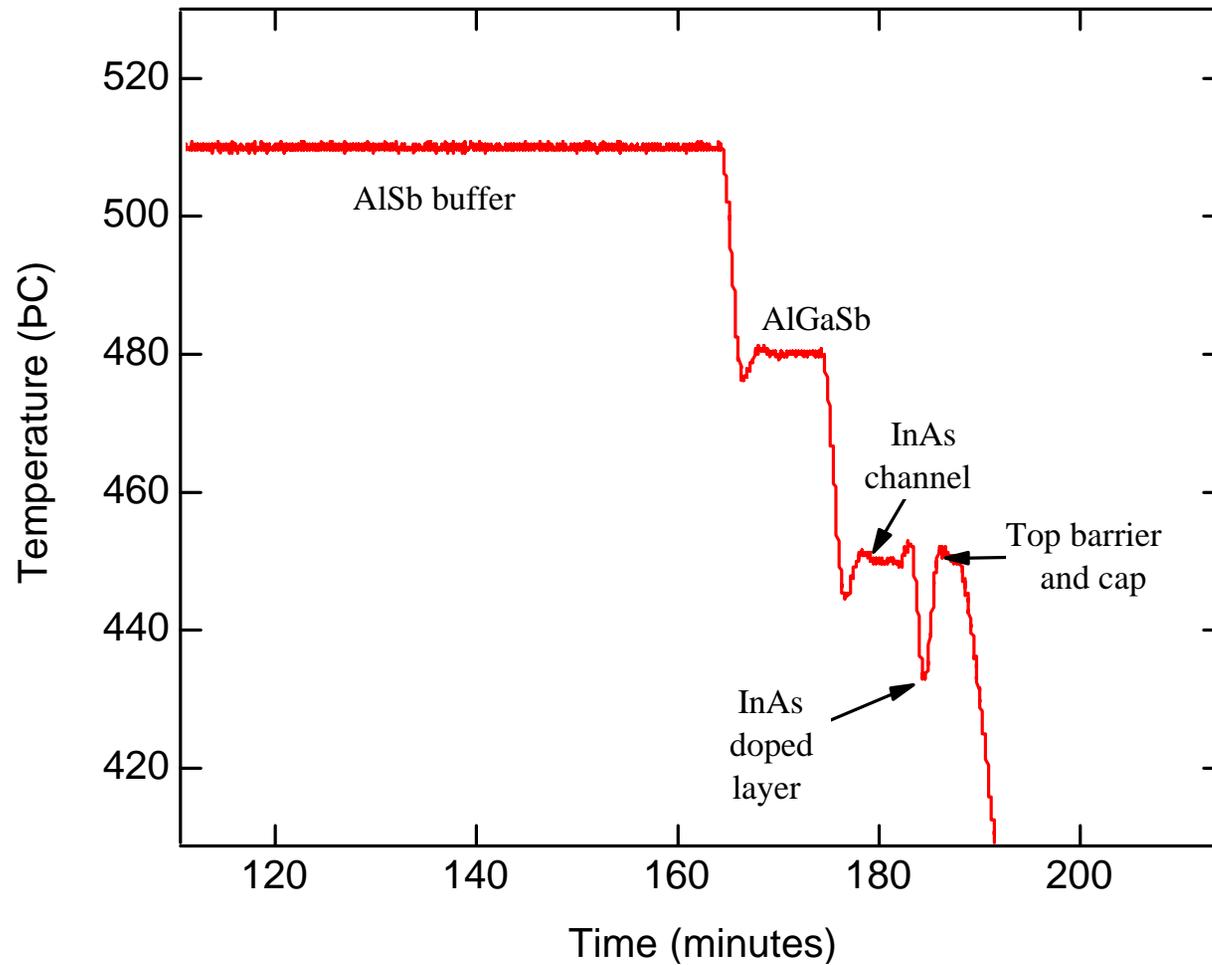
# SUBSTRATE TEMPERATURE IS SENSED BY ABSORPTION-EDGE SPECTROSCOPY (ABES)

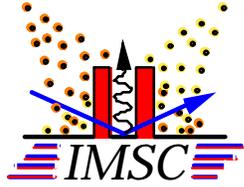


- Detector
- Spectrometer
- Lock-In Amp

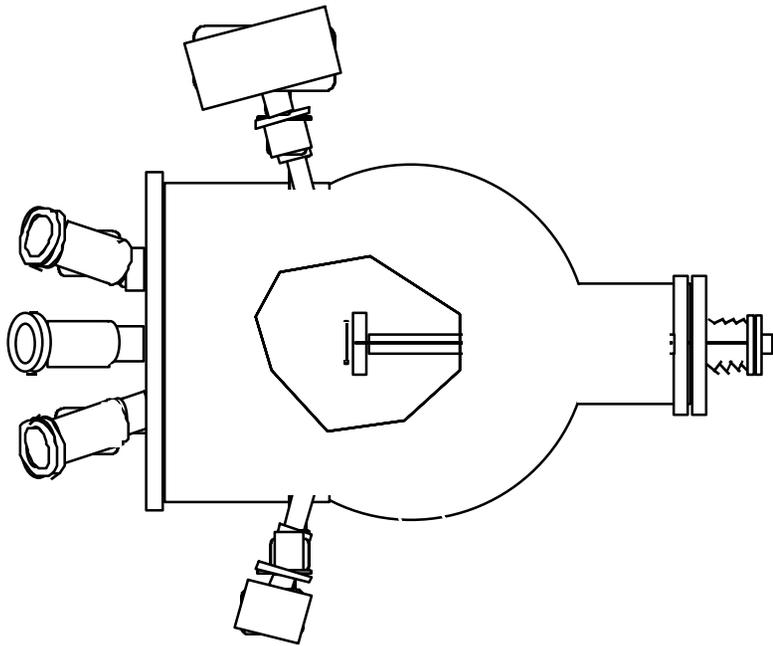


# Substrate temperature regulated during InAs/AlSb HFET deposition

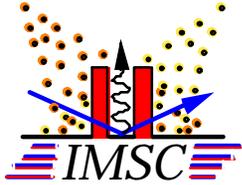




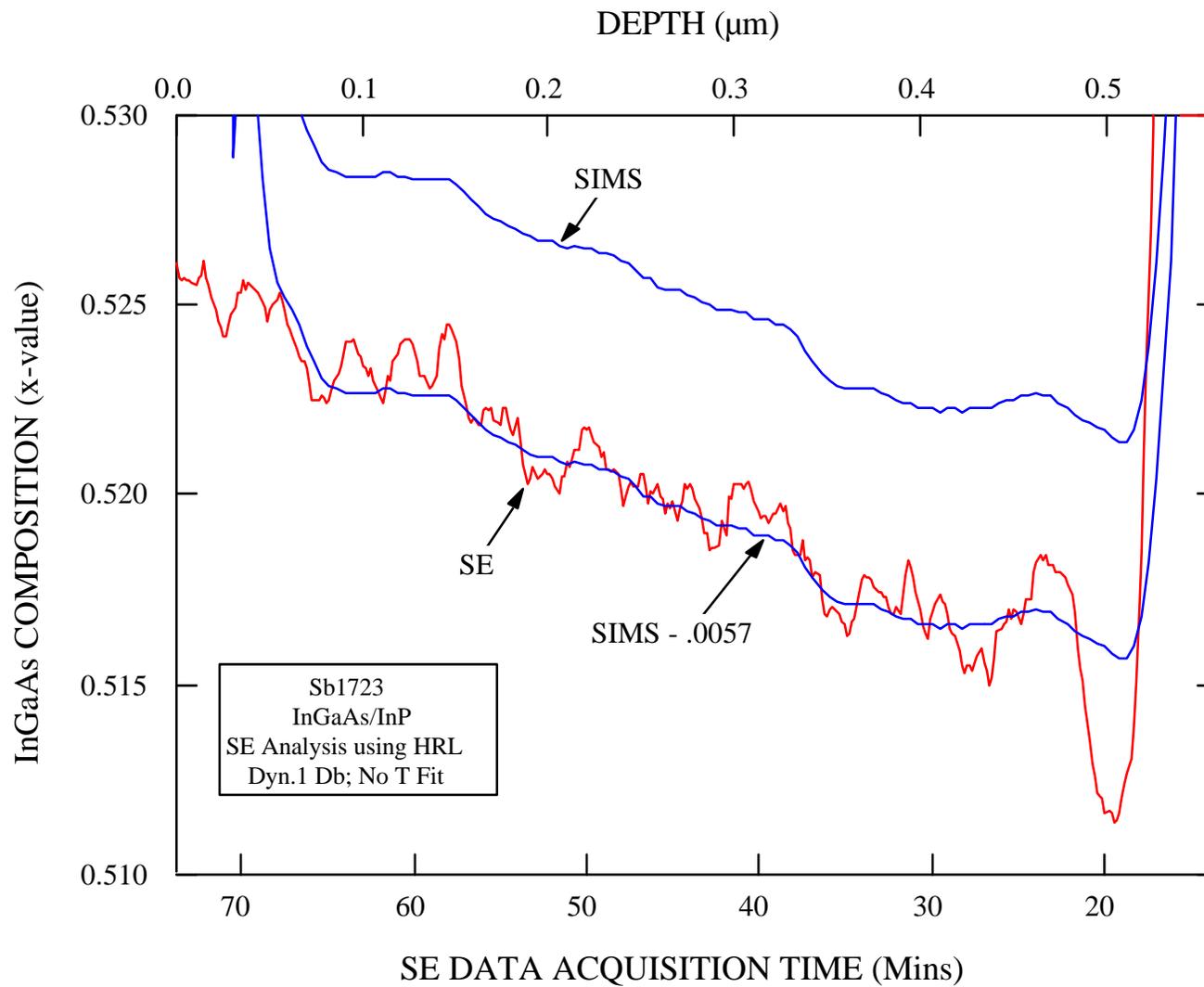
# SPECTROSCOPIC ELLIPSOMETRY FOR ALLOY COMPOSITION CONTROL

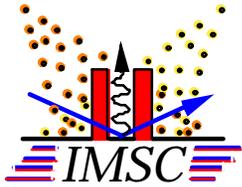


- JA Woollam M88 System
- Low wobble sample holder
- Real-time, *in situ* analysis
- Can be utilized for
  - alloy composition
  - substrate temperature
  - layer thickness

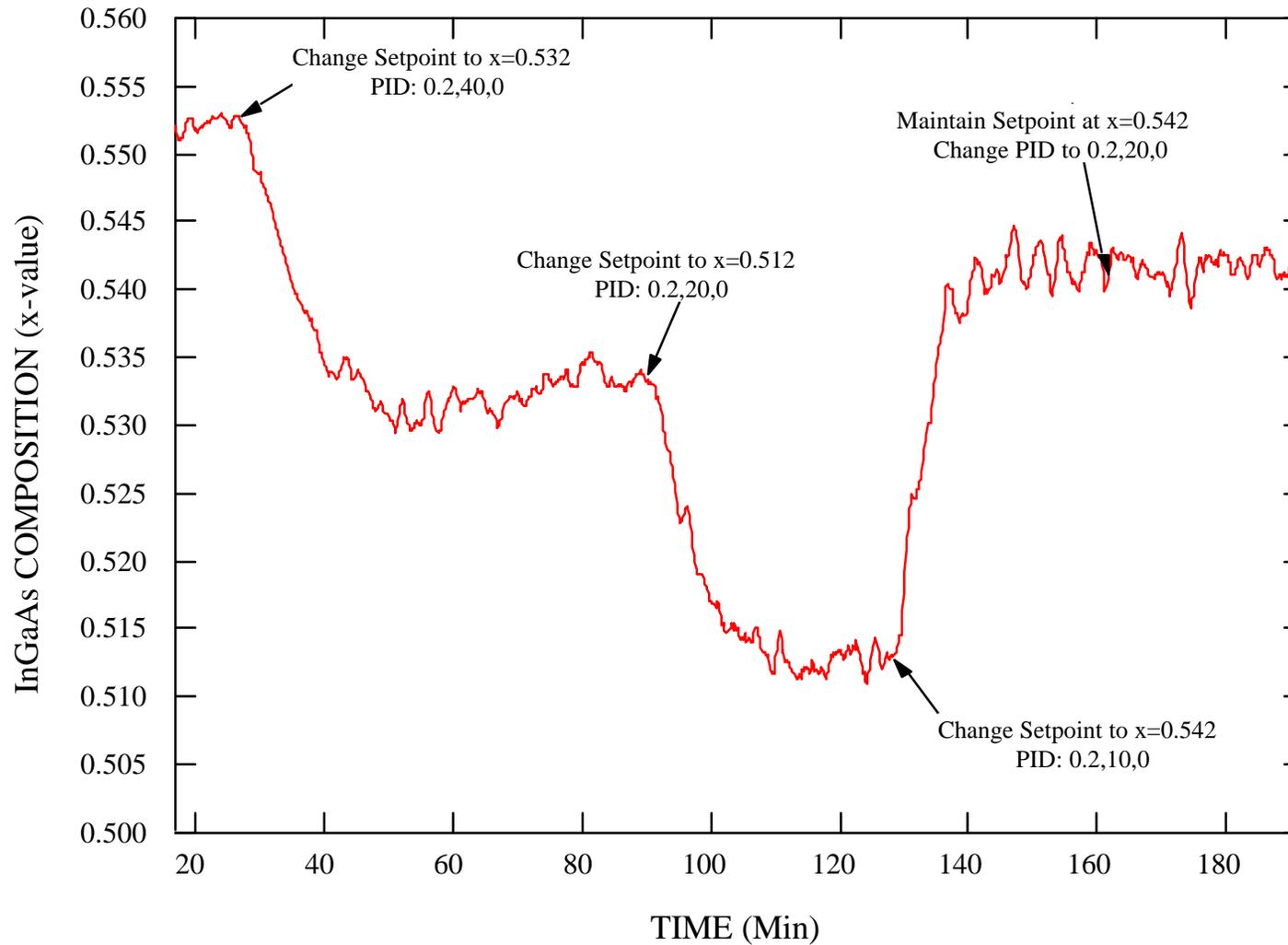


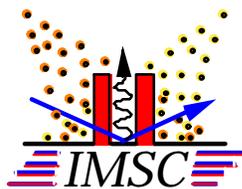
# InGaAs Composition Profile Accurately Determined *in situ* by SE



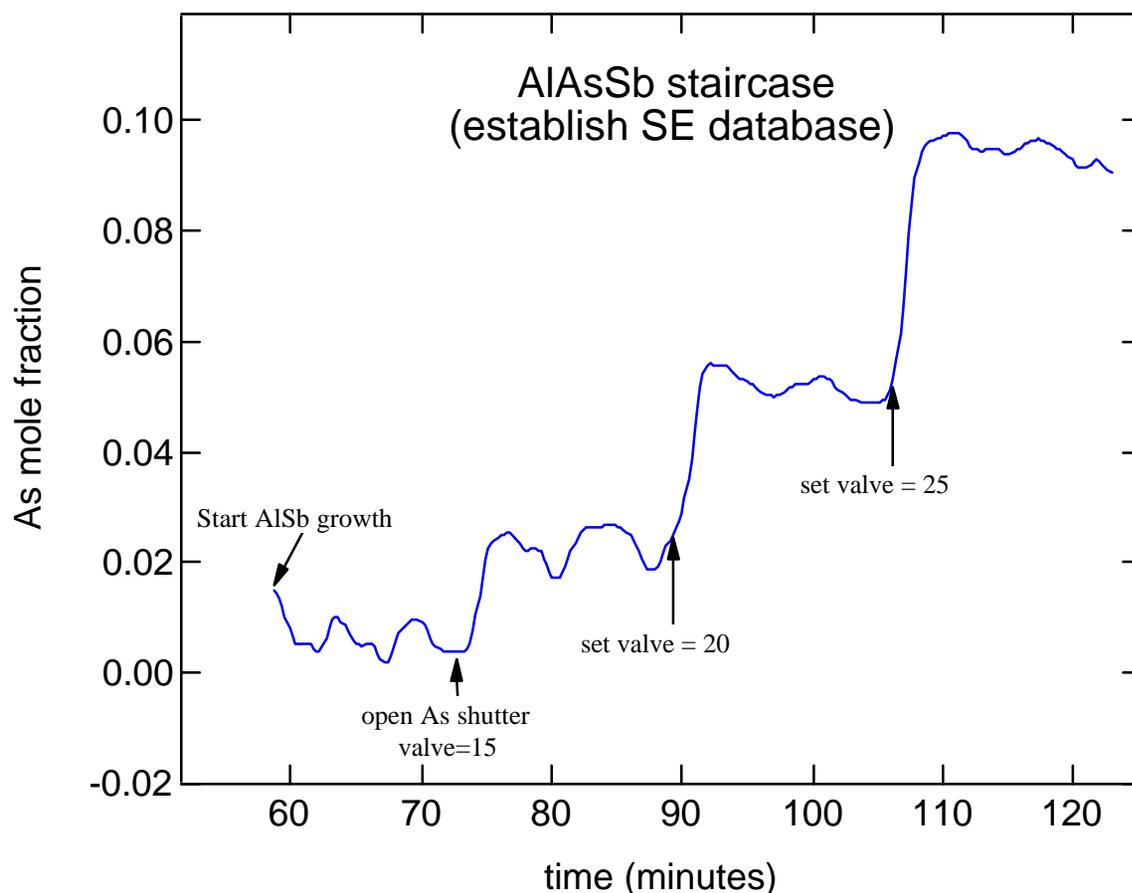


# Demonstration of Real-Time InGaAs Comp. Control Based on Nested PID Approach





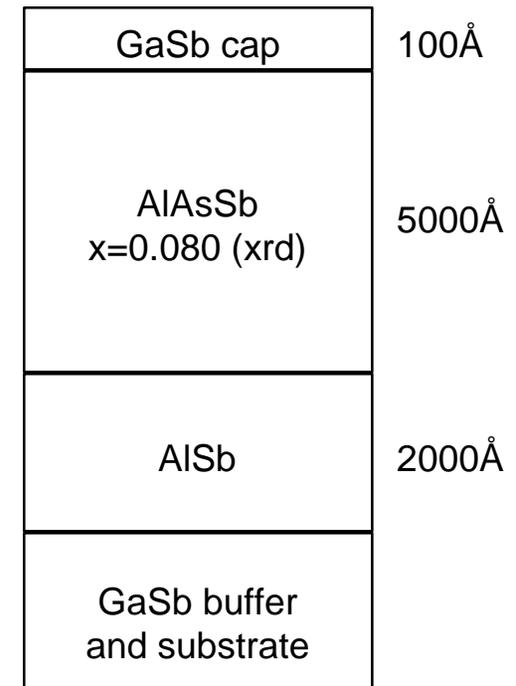
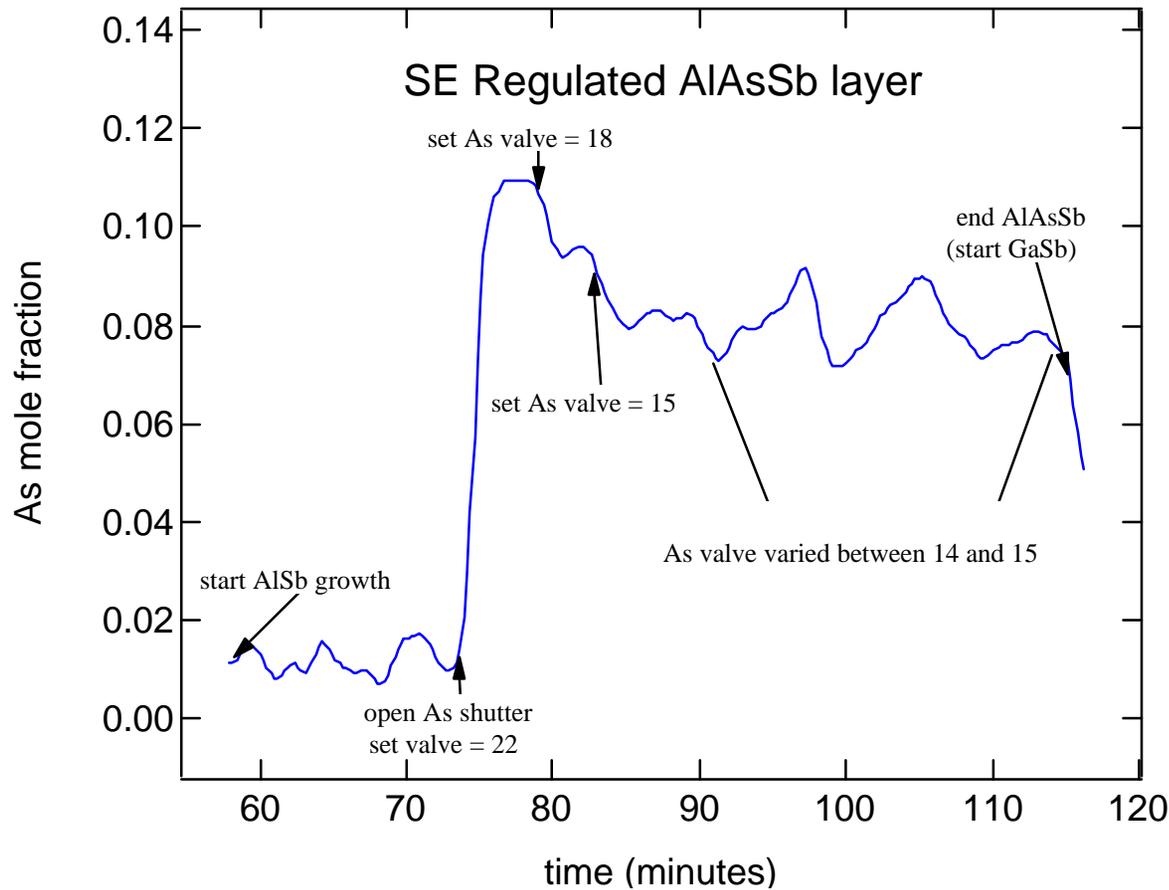
# Application of Spectroscopic Ellipsometry to control group V alloy composition



GaSb cap	100Å
AlAsSb $x=0.096$ (xrd)	2000Å
AlAsSb $x=0.053$ (xrd)	2000Å
AlAsSb $x=0.024$ (xrd)	2000Å
AlSb	2000Å
GaSb buffer and substrate	



# Application of Spectroscopic Ellipsometry to control group V alloy composition



# ISSUES FOR HIGH PERFORMANCE RITD-BASED CIRCUITS

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- **Circuit fabrication technology is relatively immature**
- **State-of-the-art circuit speed exceeds testing capability**
- **Significant technical hurdles remain for circuit design frequencies in excess of 100 GHz**
- **Technology breakthroughs needed to make commercial applications practical (e.g., heterogeneous fab)**